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A SIMPLE METHOD FOR TESTING MEASURING MACHINES AND MACHINE TOOLS

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A SIMPLE METHOD FOR TESTING MEASURING

MACHINES AND MACHINE TOOLS

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INTRODUCTION

LLNL has developed a simple method for testing coordinate measuring machines and machine tools. It is called the Magnetic Ball Bar (M.B.B.). There are two versions. The first version is called the Fixed Magnetic Ball Bar (F.M.B.B.) (Figure 1). The fixed version is used to test the accuracy of manually actuated, low friction coordinate measuring machines as well as computer controlled point to point measuring machines. The second version is called the Telescoping Magnetic Ball Bar (T.M.B.B.) (Figure 2, 3). The telescoping version is used to test the accuracy of numerically controlled lathes, milling machines, robots and servo driven contouring measuring machines. Both versions are based on the remarkable, 2 microinch, rotational accuracy that can be achieved with a high quality chrome steel ball pulled into a tri-hedral socket with a permanent magnet. The magnetic socket was first developed at A.W.R.E Aldermaston in 1959 by Frank Roberts and his colleagues. It has been in use at LLNL since 1960 for a variety of gaging applications.

System accuracy of the M.B.B. ranges from .5 to 50 microinches depending on the size and if used for 2 axis or 3 axis. Size range is 4 inches to 48 inches and larger. The device can be hand carried. Cost is approximately $2,000.00 for the fixed version and $4,000.00 for the telescoping version when made in small quantities. A test can be carried out in a time period of less than one hour.

The M.B.B. is fast, simple and powerful. It is not, however, a complete test. A machine could show zero error on the M.B.B. test and still be defective. As a minimum, particularly for acceptance testing, the M.B.B. must be supplemented with gage blocks, step bars, or laser interferometers to establish the displacement accuracy of the slides. Depending on the particular machine design, other tests such as straightness, squareness and parallelism must be included. The M.B.B. provides a means of quickly approximating the two or three dimensional accuracy of a machine. Because of its low initial cost, simplicity of set-up, high accuracy, and self checking features it is a very cost effective method for routine testing of machines during their life. It would be feasible, for example, to establish a program to test every machine tool and every measuring machine in a shop every few weeks.

MEASURING MACHINES

Background, Advantages of the F.M.B.B.

The idea of testing coordinate measuring machines with ball bars is not new. The National Physical Laboratory in Teddington, The National Engineering Laboratory in East Kilbride, the Cranfield Unit for Precision Engineering and the L. K. Tool Co. have all worked with ball bars for a number of years.

A simple ball bar consists of a bar connecting two spheres. The bar is clamped to the machine table at some angle to the axis of the machine. The machine is asked to measure the distance between the centers of the spheres. The bar is then unclamped, rotated to another angle, reclamped, and the distance measured again. Differences in the measured length are regarded as machine error.

The M.B.B. does not require clamping and unclamping and is therefore much faster. This additional speed allows the measurement of more points in the work zone. Tom Charlton, of the National Bureau of Standards in Washington, D.C. has taken data on a coordinate measuring machine on-the-fly with the F.M.B.B. by giving the machine a push and asking the computer to read out at fixed time intervals. Hundreds of data points were taken in a few minutes. The strength of the magnets and stiffness of the bar are quite adequate to provide the force necessary to guide the machine on a circular path, see Figure 4.

Another advantage is that the measurements are taken with respect to one common point which allows better understanding about the possible sources of error.

Don Lane and Vince Mangano of LLNL recently used the F.M.B.B. to specify and perform factory acceptance tests on a new coordinate measuring machine. The specification called for 700 microinches total error on a 13 inch bar. The initial test showed 1,440 microinches error, the majority of which occurred in a half inch portion of the work zone. The problem was quickly traced to a bad Moire scale on the X-axis. The scale was replaced and the error reduced to 660 microinches. The original scale had previously passed a laser interferometer test at one inch increments. A simple ball bar <u>might</u> have detected this problem, but could not have led to the intuitive diagnostics that were possible with a fixed reference point.

Another advantage of the F.M.B.B. is that it tests machine geometry independently of the sensor used to detect the workpiece. Detecting the center of balls on a simple ball bar is not a simple matter. The stylus size and sphericity and the sensor mechanism all contribute error. Some people argue, however, that the complete system should be tested and not just a part of it. This argument definitely has some merit. The M.B.B. can fortunately be used in an optional mode to include the sensor error by using only one magnet which is stationary and supporting the free end of the bar with a supplementary bracket that leaves the ball exposed for sensing by trigger probes. This mode of operation (single magnet) is a necessity for some types of computer controlled point-to-point measuring machines that do not have the disengageable drives that permit the double magnet mode to be used and do not have the continuous path contouring capability that permit the Telescoping M.B.B. to be used. The single magnet mode is slow, but it is still twice as fast as a simple ball bar and has the advantage of a common reference point.

Tom Charlton has recently developed a technique, Figures 5 and 6, to support the free end of the bar in a variety of locations in the work zone. It consists of a screwed together, adjustable length aluminum post which has two balls and a magnet at the top of the post to support the bar. The post can be varied in height and moved around the table to provide hemi-spherical coverage.

OPERATING PROCEDURES

Double Magnet Version for Manual Machines

Operating procedures can be rather boring, but they do a job of communication that is hard to duplicate. These procedures are included to assist the reader in a process of critical evaluation of the M.B.B. A typical operating procedure taken from a recent LLNL specification for a 26" x 16" x 13" manual machine is reproduced as follows:

"Clamp the fixed magnetic socket to the table. Install the free socket in the probe holder using the tapered adapter. Install one ball of the 8-inch ball bar in the fixed socket. Release the X, Y, Z slide locks and move the free socket to engage the ball that is in the fixed socket (Figures 7, 8). Rotate the ball bar while watching the readouts to verify that there is no dirt under the socket seats. Zero the readouts. Carefully disengage the free socket from the fixed ball, move outward to the free ball, and carefully engage the free ball (Figure 6). Adjust the counterweight on the Z axis to just support the weight of the ball bar. Record the X, Y, Z readings. Move the free socket to a number of other positions and record the X, Y, Z readings. Calculate the square root of the sums of the squares of these readings which should represent the center to center distances of the balls. Move the fixed socket to other positions and reclamp it. Rezero the readouts as described above, record the X, Y, Z values at other positions of the free socket and calculate the center distances. Determine the range of center distances at all positions of the fixed and free socket. If the range or variation is out of tolerance, the test must be repeated as often as necessary, averaging the worst points, to determine the existence of a systematic error."

The above procedure does not specify the number of data points to be taken. If the specification applies to all points in the work zone, the buyer should be free to test as many points as he wishes as long as he is on his own time or paying for time at the factory. The emphasis should be on finding the worst points as soon as possible. The worst points are then measured repeatedly to eliminate or average stray data.

Single Magnet Version for CNC Machines

The following procedure is speculative since it has not yet been fully tested:

"Clamp the fixed socket to the table. Install one ball of the ball bar in the fixed socket. Rotate the bar to be sure it is seated. Move the machine under manual control and take, say, 5 readings on the fixed ball using the trigger probe. Calculate the center of the ball. Lift the free end of the bar and support it with the two balls and magnet at the top of the bar support post (Figure 4). Take another set of trigger probe readings on the free ball. Calculate the center of this ball, then calculate the distance between ball centers. Slide the bar support post to different locations. Take additional readings and calculate center to center distances."

Rotational Accuracy of Ball and Socket

The rotational accuracy of the ball and socket can be tested in two ways. Figure 9 shows a setup on a roundness measuring machine. One socket is clamped to the rotating table and centered. The free end of the bar is supported in a notch in an anti-rotation flexure consisting of a piece of sheet metal clamped to an angle plate. Figure 10 is a polar chart showing a 4 microinch combined rotational error of the spindle of the machine and the ball and socket. The machine contributes about 50% of this error.

The second method of testing is not quite as conclusive but only requires the availability of a sensitive indicator. Figure 11 shows the setup for indicating the ball in its own socket. Multiple locations of the indicator with respect to the socket and rotations of the ball in the socket will give a good idea of the rotational accuracy. This method can be useful in responding to challenges in the field. Extra balls, glued in adaptors, are provided in the carrying case, Figure 12, for quick substitution should a ball become damaged and fail the test.

Effect of Ball Size Differences

The balls must be identical in size and spherical, but the actual size has no effect as long as the 3 point spherical socket seats match the balls. The error created by non-identical balls is not obvious. Jim Hamilton and Bob Berg, of LLNL, has analyzed the effect and determined the following: (1) there is no error for traces taken in the X, Y plane, (2) the error in the X, Z and Y, Z plane is 5/4 $(R_1 - R_2)$. Figure 13 illustrates the problem. Assume that the free ball is smaller than the fixed ball and that the bar is horizontal (centerline of balls parallel to X axis). When the free socket is engaged with the free ball (position 2) the readings are $X = L$, $Z = -E$, not zero. When the free ball and socket are moved to position 3 (vertical bar) the readings are $X = 0$ and $Z = L - E$. The differences in the calculated length of the bar, using these false readings, is $5/4\ (R_1 - R_2)$.

The F.M.B.B. can be checked during set up for matched balls. After zeroing the free socket on the fixed ball, turn the ball bar end for end and note the Z axis reading. No change in Z means that any ball size error is less than half of the machine resolution and may be neglected.

Slide Squareness Sensitivity

We have recently realized that hemispherical test patterns do not provide adequate sensitivity to squareness error. Figure 14 illustrates the problem. At position #1 the length of the ball bar varies one for one with unwanted movement of the Y axis in the X direction. At position #2 the influence of Y axis errors on X show up on the calculated ball bar length at $\cos 45^{\circ} = .707$ or 71%. At this point the Y axis has moved only 71% of its travel. At position #3, where the Y axis has moved its full travel, the influence is zero. It can be argued that slide squareness measurements are easy to make with readily available hardware and that the machine should be pre-qualified with regard to squareness before testing with the F.M.B.B. It is possible, however, to enhance the squareness sensitivity of the F.M.B.B. by selecting a bar that is equal in length to the longest travel of the machine and moving through an angle that will exercise the full travel of the other axis. See Figures 15 and 16. For example, a 26" X-axis, 16" Y-axis, 13" Z-axis machine would use a 26" bar for testing X, Y squareness that would rotate through an angle of plus and minus $\theta = \sin^{-1}(8/26) = 18^{\circ}$ for full travel of X and Y. The sensitivity is then $\cos 18^{\circ} = .95$ or 95% of the error that would be revealed by a conventional square. Sensitivity for Y-Z squareness is 90%. For X-Z squareness it is 97%. This loss of sensitivity can be regarded as a minor setback when it is realized that no assumptions are necessary about the squareness of the square. Figure 16 shows the arrangement for testing X, Y and X, Z squareness in the same setup. The magnetic sockets must be mounted horizontally for this test. This procedure will be incorporated in future LLNL specifications.

Z-Axis Roll

Rotational movement of the Z axis in roll is of serious concern when the probe stylus is offset from center. If roll is present, squareness of Z travel to X and Y will depend on the stylus offset distance. A test for this condition can quickly be made with the M.B.B. by simply offsetting the probe socket from center and retesting squareness. The weight of the bracket that is needed for the offset is of some concern for cantilever arm machines. This effect can be minimized by making the two squareness tests that reveal the roll motion in the X-Z plane rather than the Y-Z plane, since sag of the cantilever arm is in the non-sensitive direction.

Sag Errors

Sag error for long bars is an obvious concern. Jim Hamilton, of LLNL, has made the necessary calculations to show that the .75" dia. by .065" wall, 48" long bar used in the LLNL design will sag .027" at the center when horizontally supported at each end. The foreshortening due to this sag is, however, only 35 microinches. What actually matters is the difference in length due to gravity between the horizontal and vertical positions of the bar. If the Z axis counter balancing system is adjusted to just support the free end of the bar in the horizontal position it is then supporting half the weight of the bar. When the bar is moved to the vertical position, the counter weight is still supporting half the weight of the bar. The upper half of the bar stretches in tension while the lower half compresses an equal amount. The length of the bar is then the same as it would be in zero gravity. The 35 microinches of horizontal support foreshortening then shows up as full error. If this error is of concern it can obviously be reduced by using larger diameter tubing. The sag situation for the T.M.B.B. is different and will be discussed later.

Diagnostics

As discussed above, the M.B.B. offers the possibility of subjective diagnostics. Definitive diagnostics based on computer analysis of the huge amounts of data that can be generated remains a tantilizing, but remote, possibility. Tom Charlton, of NBS, has done some research in this area. After some initial enthusiasm he is now convinced it is a very difficult problem. It appears, however, to be an excellent theoretical research project. The goal would consist of extracting the seven constitutents of two axis machine error from as large a data base as desired. These constituents are: (1) X displacement, (2) Y displacement, (3) X straightness, (4) Y straightness, (5) X to Y squareness, (6) X angular motion and (7) Y angular motion. If this goal is not possible, a second goal would be the determination of assumptions about the various errors that would make some definitive diagnostics possible.

MACHINE TOOLS

Background, Advantages of the T.M.B.B.

The idea of testing machine tools with circular masters is not new. In 1958 LLNL developed the twin disc check for testing tracer lathes[1]. This technique used two, identical, but unknown size steel discs as masters, Figure 17. The discs were ground side by side on dead centers on a fixture on a cylindrical grinder and were round within 15 microinches. One disc was used as a template. The second was bracketed to the spindle. An electronic indicator (LVDT) supported in a single axis flexure from the tool post was used to indicate against the second disc. A perfect tracer lathe would show zero error. The advent of numerical control eliminated the need for the first disc, but required the size of the remaining disc to be known. Single disc checks have been used routinely at LLNL for specification, acceptance testing and maintenance of N.C. lathes for the past 19 years. The single axis flexure pickup is simple to set up and use but it limits the included angle that can be followed to 90°. It also has a continuously varying cosine error that must be taken into account.

In 1963 a pick up was designed at LLNL that could be used to sweep a 360° path. It used the rotatable stylus principle, Figure 18. The LVDT pick up was supported from a precision ball bearing spindle and adjusted so the stylus ball center was on the axis of rotation. Outrigger pads, bearing against the disc, automatically kept the LVDT cartridge normal to the disc. The system worked well and was free of cosine error, but it was slow to set up and never used extensively.

Advantages of the T.M.B.B.

The T.M.B.B. performs the same basic task as the disc check but has the following advantages: (1) it is less expensive, (2) it can be used for much larger machine tools, (3) it can be used for 3 axis of continuous path movement, (4) it can be used for 360° traces, (5) there is no cosine error, (6) it is easier to carry and less susceptible to damage, (7) it is more accurate, (8) it is less likely to cause damage to the machine in case of a runaway, (9) it is more applicable to robots, and (10) accuracy can be verified in the field.

OPERATING PROCEDURES

N.C. Lathes, Two Axis Tests

Figure 19 shows the T.M.B.B. setup on diamond turning machine #2 at LLNL. The spindle slide (Z axis) has a total travel of 9 inches. The X slide has a travel of 13 inches. A rotary table is used to maintain the tool normal to the work (B axis) but the B axis is not active in this test. If the free socket were centered on the B-axis a 3-axis test could be made. The tool holder has been removed from the rotary table to make room for mounting the free socket so that a 360^0 trace can be made. A typical procedure is as follows:

"Select the appropriate length extension bars from the kit and screw them together with wrenches. Measure the overall length across the crests of the balls when the L.V.D.T. is at zero with an outside micrometer. (This step is easier if the bar is vertical, with the flexure down, clamped in a vee block at one of the hex joints. The weight of the flexure ball provides mechanical bias. As the micrometer is gradually "closed" the meter will move from off-scale to the left to zero.) Subtract the nominal diameter of the balls from the micrometer reading. This value is a rough approximation of the center to center distance of the balls. (The only consequence of error in this measurement is that the meter will not be zero for a perfect machine and a lower magnification must be used to stay on scale.) Make an N.C. tape for a 360^0 trace using this value as the cutter center. Bracket the fixed socket to the spindle at centerline height. Bracket the free socket to the machine so that the free socket is located at a point normally occupied by the tool. Move the machine under manual control to the approximate point of what will be the 0 degree point of the 360 trace. Install the flexure ball in the stationary socket. Continuing to support the extension ball by hand move, the machine manually so the extension ball will start to fall into the free socket. Release the bar. Continue to move the machine under manual control until the extension ball is completely in the free socket and the meter is zeroed. Move the insensitive axis under manual control to "peak-out" the meter reading. Move the sensitive axis to rezero the meter. Verify calibration of the L.V.D.T. using the machine as a master by making small point to point moves under manual control. Return to zero. Disengage the extension ball from the free socket. Under tape control move the machine to the 90^{0} position. Move the machine under manual control as necessary so that the extension ball can again be engaged in the free socket and the meter set to zero. Disengage the extension ball, move the machine to 180^{0} under tape control. Re-engage the extension ball in the free socket. The meter should be within .001" of null depending on the accuracy of the outside micrometer measurement of length and the accuracy of the machine. Manually move the machine to reduce the error by one half. Disengage the extension ball, move the machine under tape control to 270^{0}, re-engage the extension ball, move manually to reduce the meter reading by one half. Adjust the meter zero control so the deflection from zero is minimized. The setup is now complete. The machine is moved under tape through 360^{0} while data is being recorded either by hand, digitally, linear recorder, or polar recorder. An adjustable speed, time based, polar recorder is useful. It must be adjusted to match the rotation of the T.M.B.B. Careful selection of the N.C. feedrate to match the known circumference of the trace and available speeds of the recorder will minimize this problem. If the data is taken by hand or linear recorder it must be replotted in polar form. Using a compass, draw a minimum diameter circumscribed circle around the error plot in the same way that is normally done for roundness charts. The maximum deviation from the minimum diameter circumscribed circle is the numerical value of the 360^{0} T.M.B.B. test."

The purpose of the polar plot and non-roundness criteria is to minimize time consuming mechanical centering. The user may decide it is faster to mechanically center in order to use linear recorder data directly, but the "non-roundness criteria" has the advantage of being well understood and unambiguous as a standard. Polar display of error can also be of help in subjective diagnostics.

The machine is relatively safe from damage in a runaway situation with this setup since the bals will automatically pop out of their sockets. The T.M.B.B. is considered expendable by comparison to the machine.

N.C. Milling Machines, 3-Axis Tests

Figure 3 shows the T.M.B.B. setup on a Sundstrand 5-axis milling machine. Only three axis are being used, but the test can be made on all five axis if desired. A 17" bar is shown. The user has a choice of programming a three axis hemispherical spiral or separate X-Y, X-Z, Y-Z, traces. The operating procedure is the same as for two axis except that the Z setup value is zero. The flexure ball should always be the free ball to minimize differential sag. Sag error for the T.M.B.B. is different than for the F.M.B.B. and is discussed in a following section. Wreck susceptibility is worse for the three axis situation unless one of the magnetic sockets is itself held with another magnet perpendicular to its base. (Not shown in the illustration.) Ball and socket rotational accuracy and methods of test are the same as the F.M.B.B. except that for the roundness measuring machine test the free ball is clamped and the flexure L.V.D.T. reads the error. Squareness sensitivity considerations are the same as the F.M.B.B.

T.M.B.B. Sag

Figures 20, 21, 22 shows a test for differential sag. The sockets were glued to a 2 inch square steel bar in the horizontal position and the meter zeroed, Figure 20. The bar was then rotated to the vertical position (Figure 21). The meter showed less than one microinch for a 17" bar! This remarkable result is the consequence of a number of effects all cancelling each other. In the horizontal position, the bar sags and pulls the L.V.D.T. coil away from the core (minus meter reading). The flexure adapter also bends tending to move the coil toward the core (plus meter reading). These effects are of opposite sign but not equal magnitude. The bar sag effect prevails (minus meter). When the system is vertical and the flexure is on top, the weight of the flexure adapter, half the weight of the flexure, and the bar itself compress the bar (in reality a 3/4" O.D. by .065" wall tube) and tend to move the coil away from the core which is supported by the upper ball (minus meter). The combined effect is zero.

When the system is rotated to the vertical with the flexure on the bottom of the stock, Figure 22, the meter reads 12 microinches plus. This is due to tension in the bar which is supporting its own weight plus the flexure adapter and half the weight of the flexure. Elongation makes the coil more toward the core which is supported by the lower ball and socket. This gives a plus meter reading. Cancellation requires the same sign and same magnitude error. It is apparent from this discussion that the flexure ball should be the free ball for sweeps in the vertical plane. The flexure adapater should be on the bottom when the T.M.B.B. is horizontal (Figure 20). Bending of the flexure when loaded with the 17 inch bar is 6 microinches. Sag of the bar is 12 microinches. Compression and tension is 6. These can add up to 24 microinches in the worst combination.

Agreement of T.M.B.B. with the Disc Check

The data from a T.M.B.B. check should, in principle, be exactly the same as from a disc check. It is important to demonstrate this agreement experimentally so that people who are familiar with disc checks will have confidence in the "new" method. A problem arises in demonstrating this agreement. The T.M.B.B. is normally used for 360^0 traces to allow the "non-roundness of the polar profile" criteria to apply. The disc check can only be made for 90^0 traces if a single axis pickup is used. The solution to this problem is to establish an absolute length for the T.M.B.B. and make a 90^0 trace. A calibrated length ball bar is the same as a calibrated radius disc. A 90^0 disc check is normally made by adjusting the error at the 0^0 and 90^0 points to zero. The same approach is used for the T.M.B.B. The results of the two tests should be the same if the two systems are perfect. The conditions for a perfect 90^0 T.M.B.B. system are: (1) the balls are perfectly spherical, (2) the L.V.D.T. is properly calibrated, (3) the center to center distance of the balls at null matches the N.C. tape, and (4) the plane swept by the balls is parallel to the X, Y travel of the machine to avoid cosine error.

The conditions for a perfect 90^0 disc check are: (1) the disc is perfectly round, (2) the stylus used for the pick up is perfectly round, (3) the radius of the disc plus the radius of the stylus matches the N.C. tape, (4) the single axis flexure L.V.D.T. pick up has no side deflection, (5) the L.V.D.T. is properly calibrated, (6) cosine error on the data is properly handled, and (7) the disc is parallel to the X, Y travel of the machine.

A comparison of the two methods has recently been made at L.L.N.L. and the agreement is within the errors expected from the above sources.

Another application for 90^0 T.M.B.B. traces is for small machines that do not have the 8" travel necessary for 360^0 traces using the 4" minimum radius T.M.B.B. Figure 23 shows a setup for a 180^0 trace on an N.C. turret lathe having only 4" of tool slide travel.

The problem of adjusting the T.M.B.B. to a known radius within a few microinches is not trivial. Figures 24, 25, 26 illustrate one technique for setting the ball centers to, say, 4 inches. It assumes that the absolute measurement of ball sizes to a few microinches is a difficult metrology problem, particularly in the field. A five inch gage block with extension blocks is modified with vee blocks glued in place so that the center of the vee blocks are parallel to the gage block in both planes. The T.M.B.B. can be placed in the vee blocks and adjusted so the distance across the crests of the balls is 5 inches at null. We really want the center to center distance to be 4 inches. By gluing vee blocks and a tri-hedral socket in the center of a 9 inch gage block we can make two, 180^0 rotation checks with the T.M.B.B. reversed between checks. The 3 data points from these checks provide enough information to determine the radius of each ball and their center distances.

Absolute calibration of center distances is a nuisance and can be avoided with 360^0 traces, but it offers some advantages and remains an option in the T.M.B.B. evolutionary process.

Status of Outside Evaluation

The American National Standards Institute (ANSI) Committee B 89.1.12 on Coordinate Measuring Machines has been studying the possibilities of the F.M.B.B. as a means of specifying accuracy and performing acceptance tests. Bill Gehner, of the John Deere Co., Ben Taylor of the Bendix Corp., and Tom Charlton and Bob Hocken of the National Bureau of Standards have been particularly active in evaluation testing. Current thinking on the Committee is to recognize the F.M.B.B. as an interim standard. It would be used in conjunction with single axis displacement measurements. Two dimensional and three dimensional ball plates will also be recognized in the interim standard as an option. The Committee is being somewhat cautious about ball plates because of their weight, calibration expense and potential for damage. Dr. H. Kunzman, Chief of Dimensional Metrology at the Physikalish-Technische Bundesanstalt (P.T.B.) in West Germany has taken an interest in the F.M.B.B. and is planning an evaluation program. The Metrology Group of The International Institute for Production Engineering Research (C.I.R.P.) is also planning a cooperative research effort on the subject.

Bob Hocken and Tom Charlton of N.B.S. are the only outside people that have evaluated the T.M.B.B. Their comments have been favorable.

Patent Status

The F.M.B.B. was first demonstrated publicly to ANSI Committee B 89.1.12 on June 24, 1980. The Department of Energy did not apply for a patent within a year from that date so it is no longer patentable.

The T.M.B.B. was first demonstrated publicly (ANSI B 89.1.-12) on March 31, 1981. The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the performance of research and development work at the Lawrence Livermore National Laboratory. A patent application concerning this invention is being prepared for filing in the U.S. Patent and Trademark Office. When and if the patent issues, the invention will be available for licensing in accordance with usual U.S. Government policy. There is no limitation on the use of the T.M.B.B. prior to the issue of the patent.

ACKNOWLEDGEMENTS

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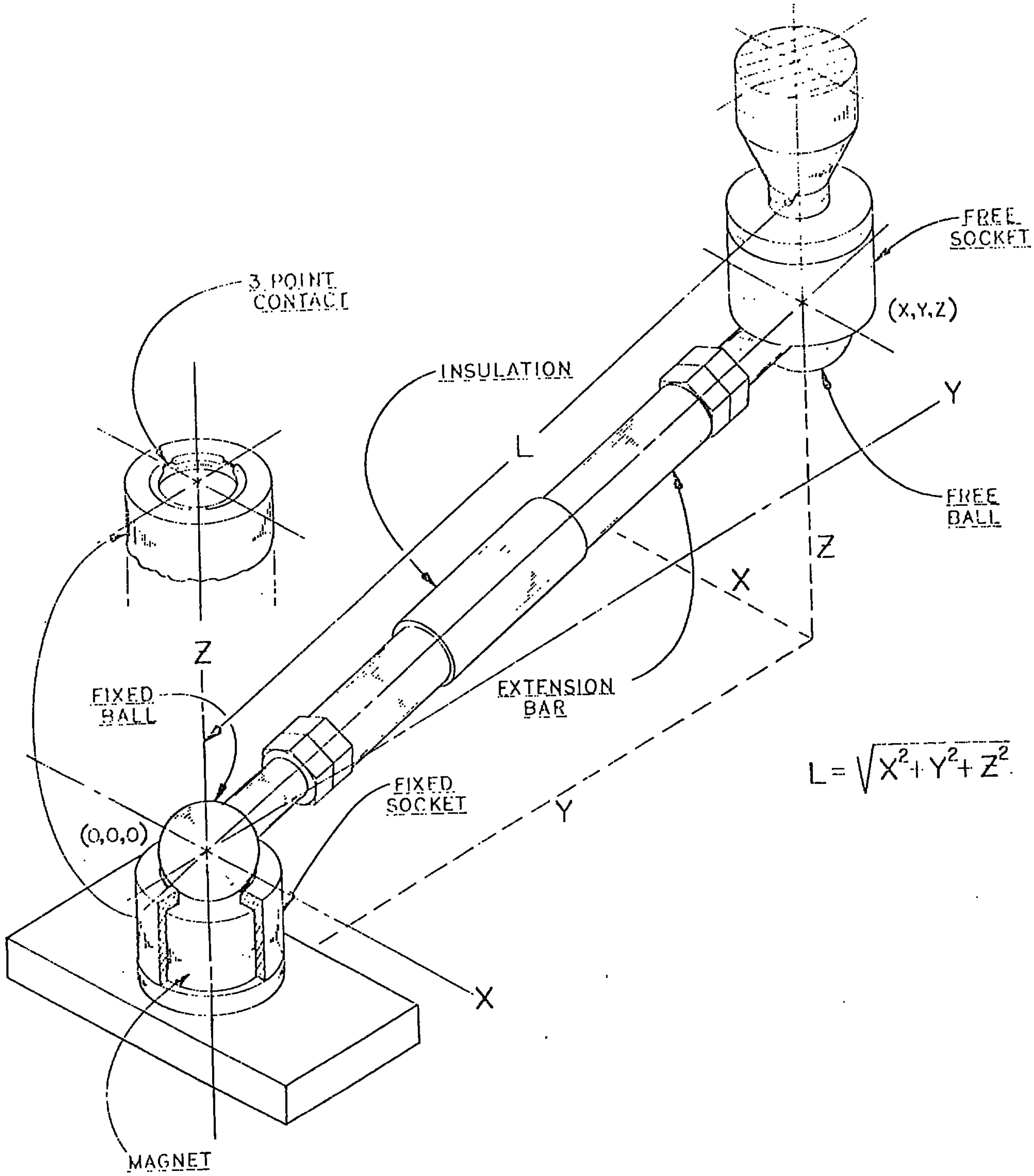
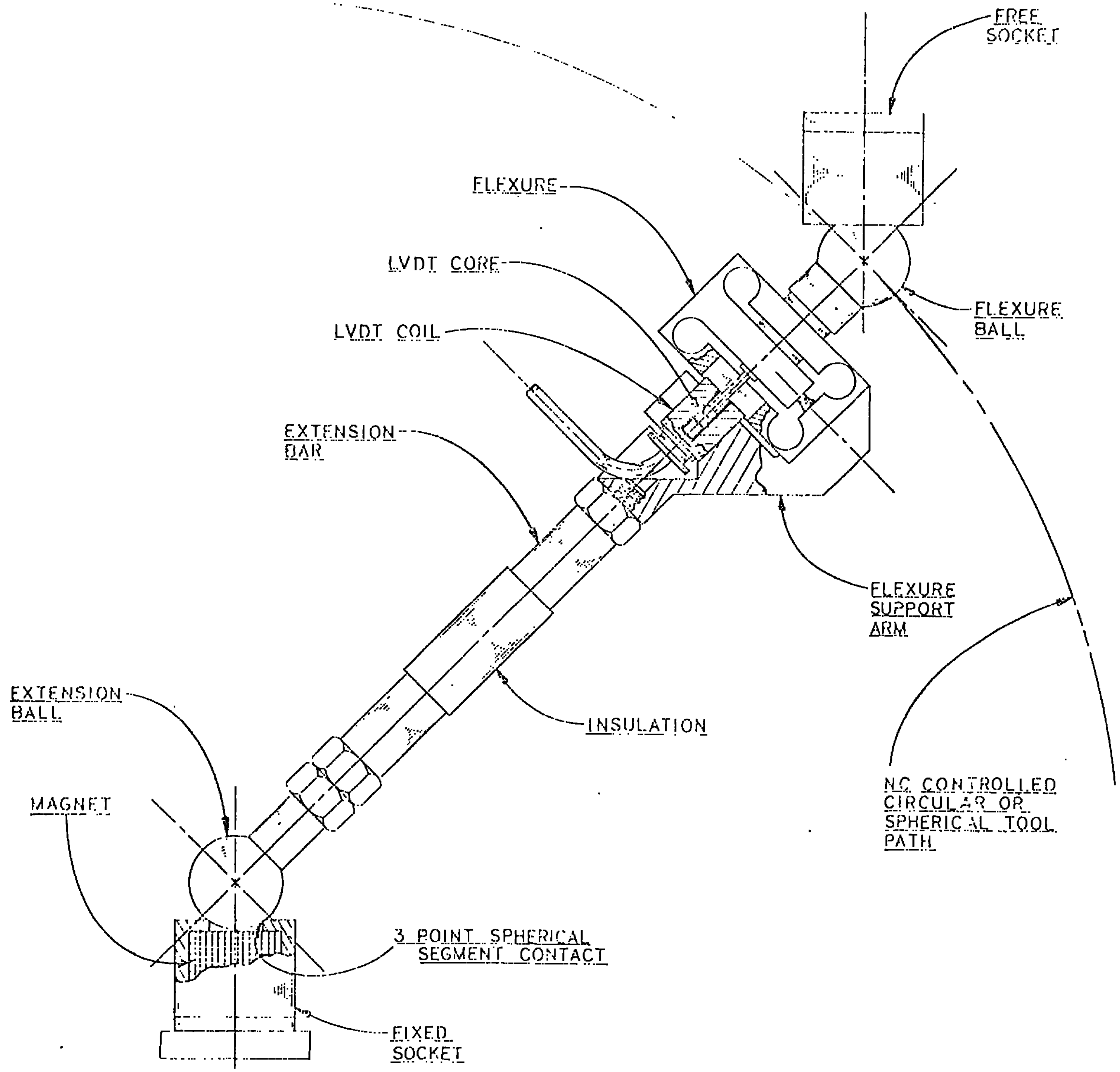


FIXED MAGNETIC BALL BAR

FIG Nº 1

DRAWN BY: VIC TARDIFF
DATE: 7 JAN 1982



TELESCOPING MAGNETIC BALL BAR

FIG Nº2

DRAWN BY: VIC TARGIFF
DATE: 7 JAN 1982

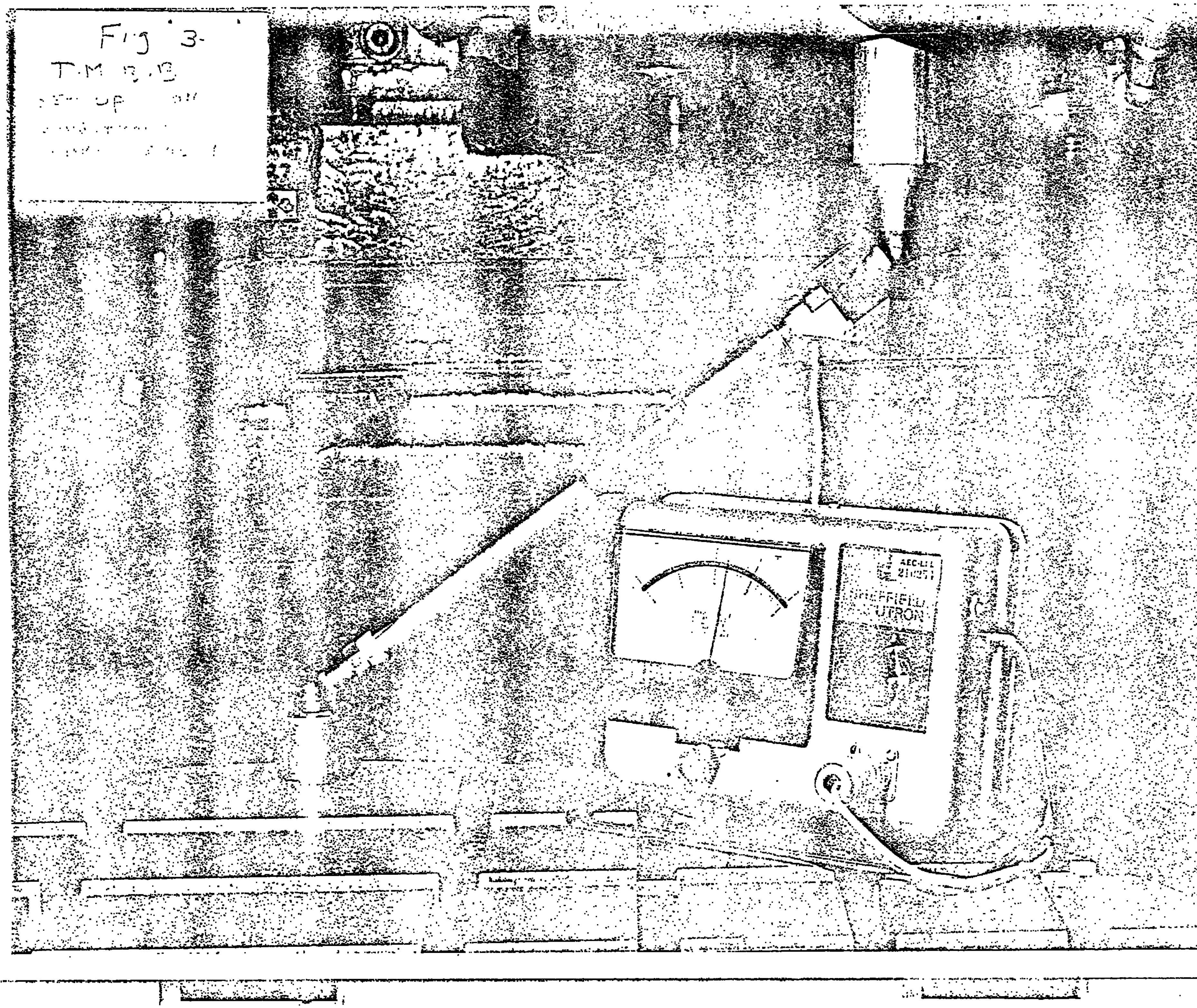


Fig 3-
UP
UTRON

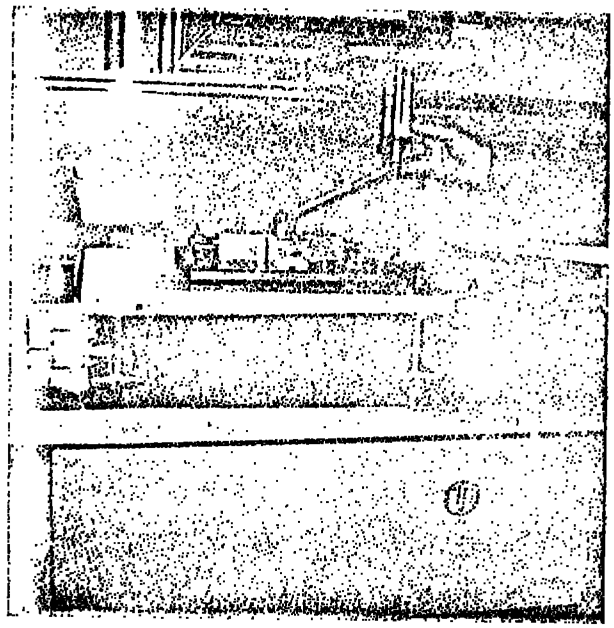


Fig 4

F.M.B.B setup on

Cordax Measuring Machine

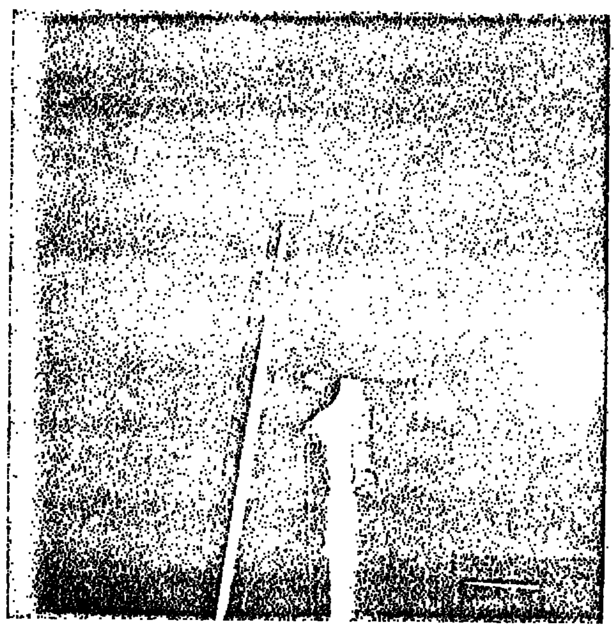


Fig 5
Two Ball Magnetic Support
For the Magnetic Version of
The [illegible] Developed By N.B.I

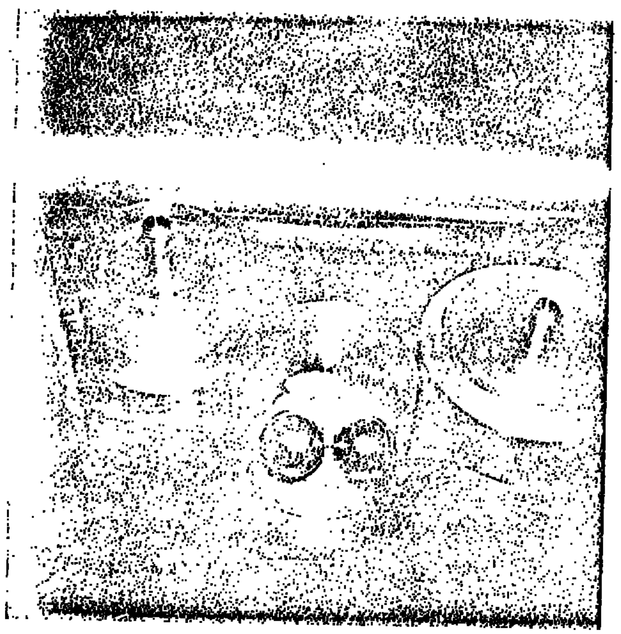


Fig 6

Close up of Two Ball
Magnetic Support For
Single magnet version of
F.M.B.B

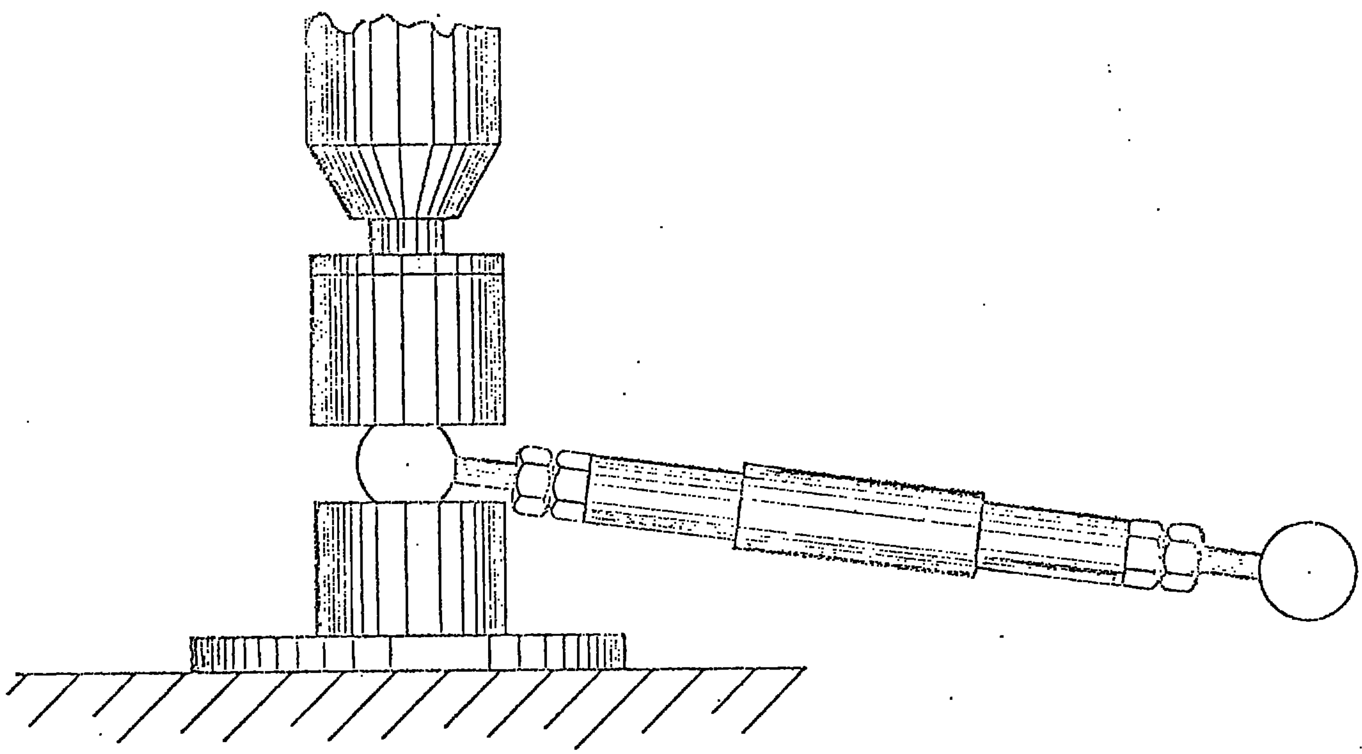


Figure ~~A4~~ 7
Schematic of Free Socket Engaged with Fixed
~~Establishing the three-axis zero point~~.
Ball to Establish Zero point

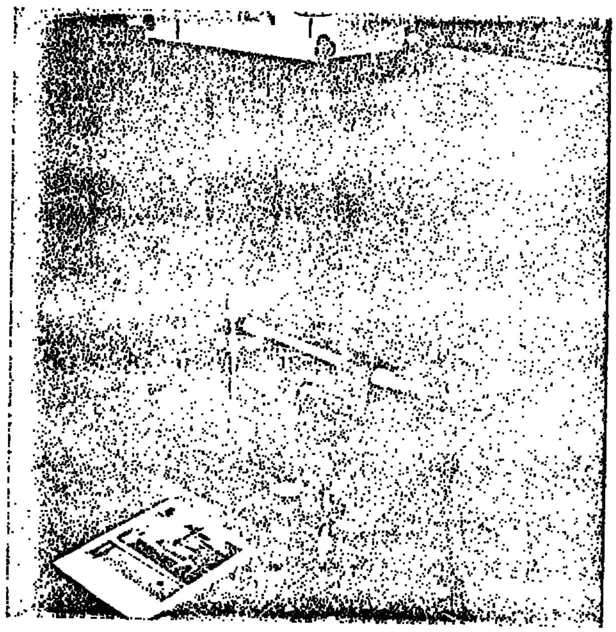


Fig 8

Free Socket Engaged with Fixed Ball to Establish Zero Point of Corday Measuring Machine

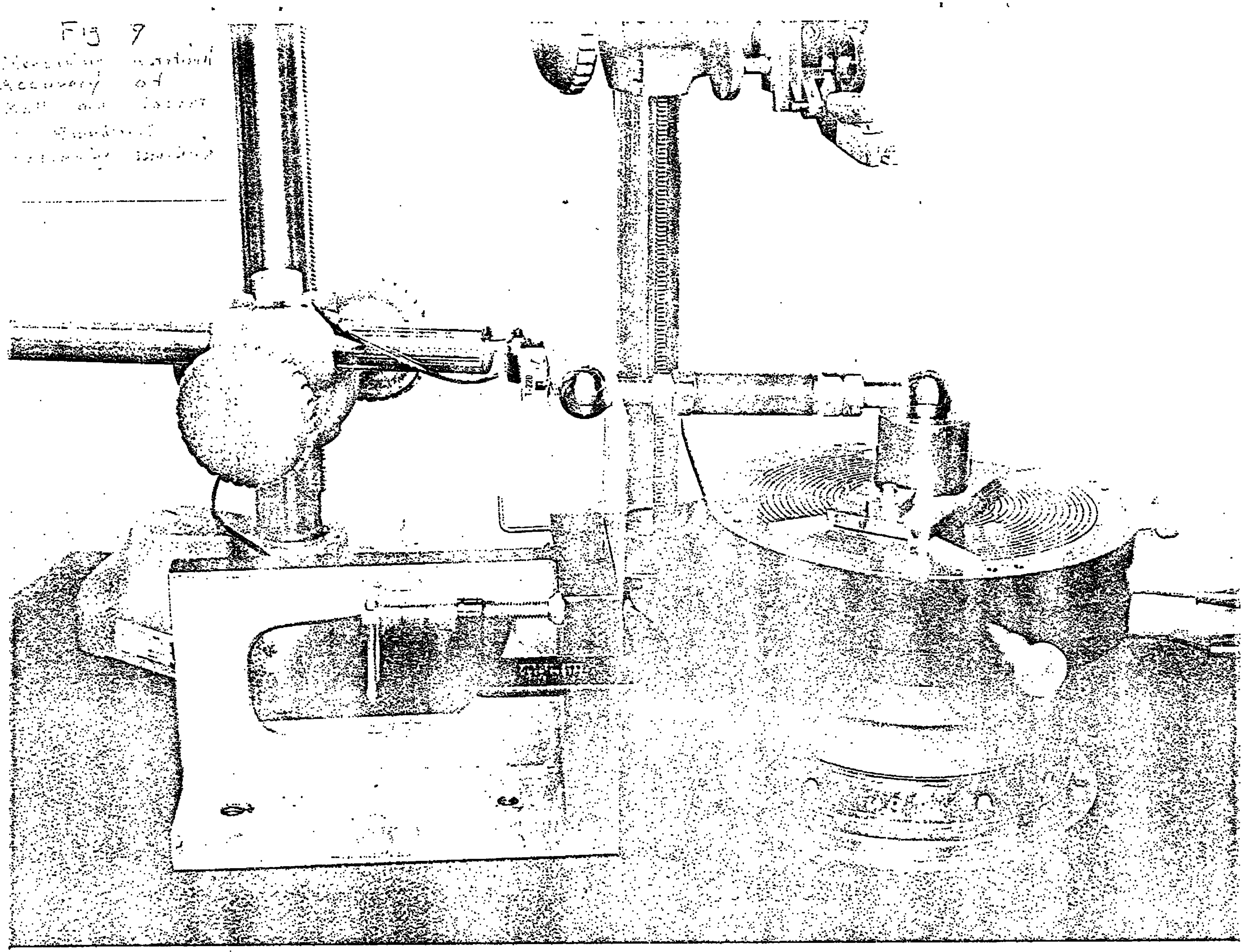


Fig 9
[illegible] Accuracy of [illegible]

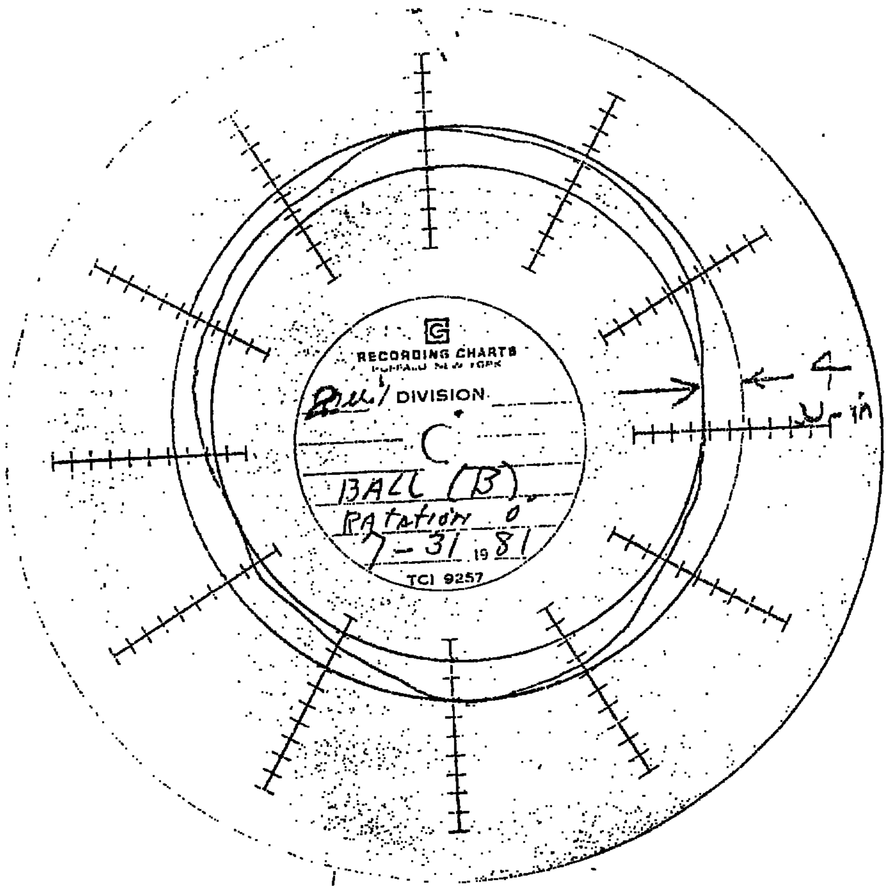
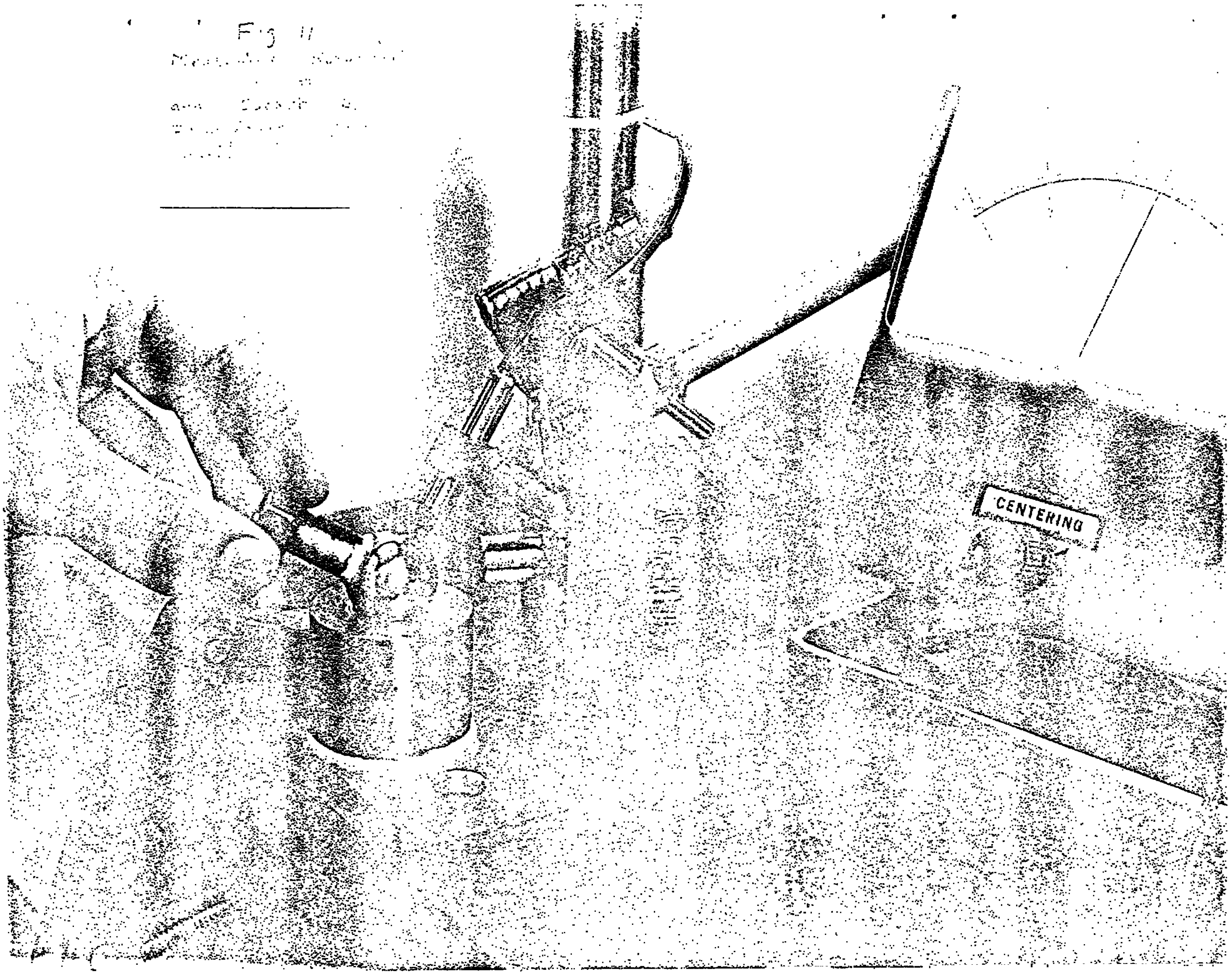
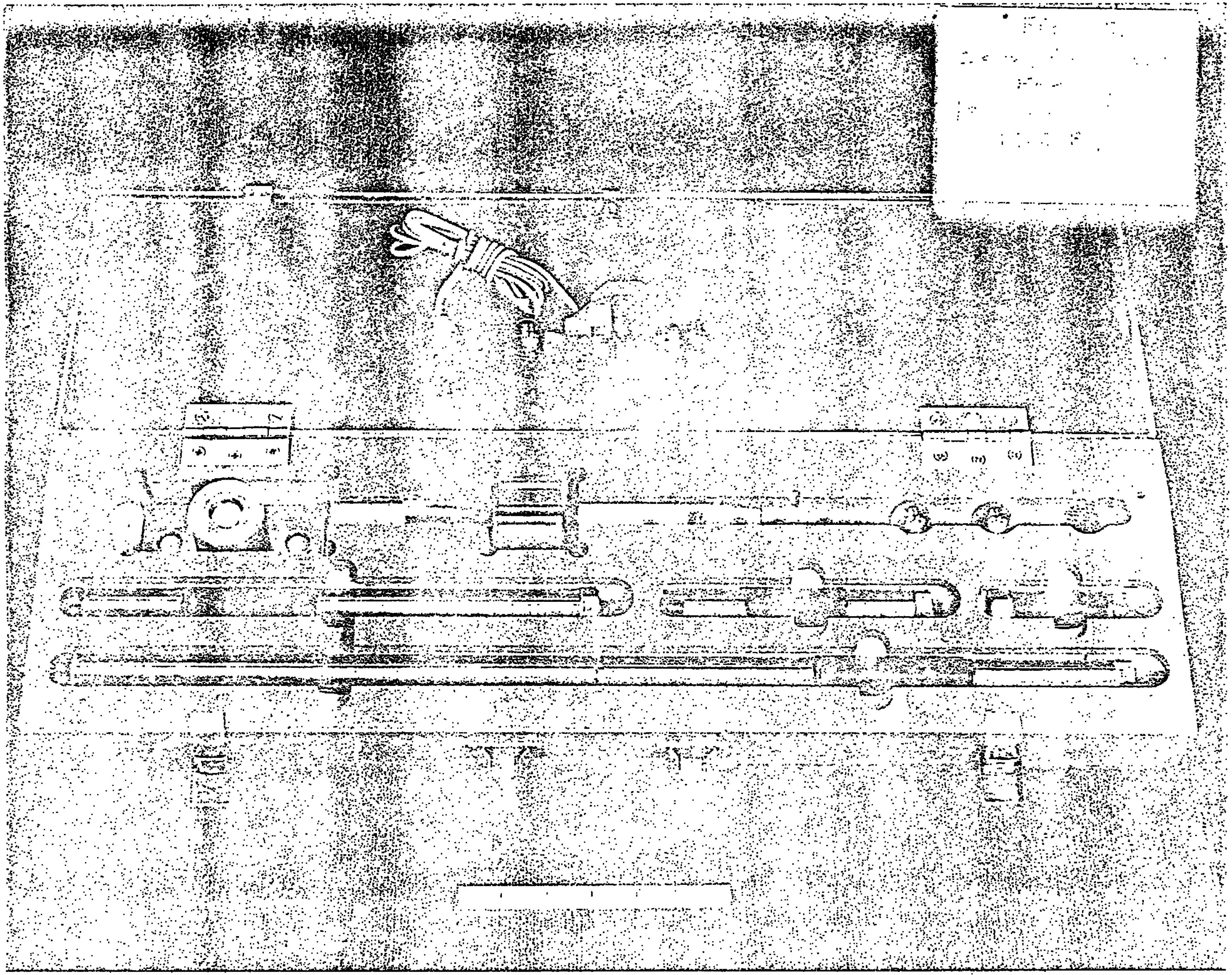


Fig 10

Polar chart of Combined Error of Ball and Socket and Roundness [illegible]

Fig 11





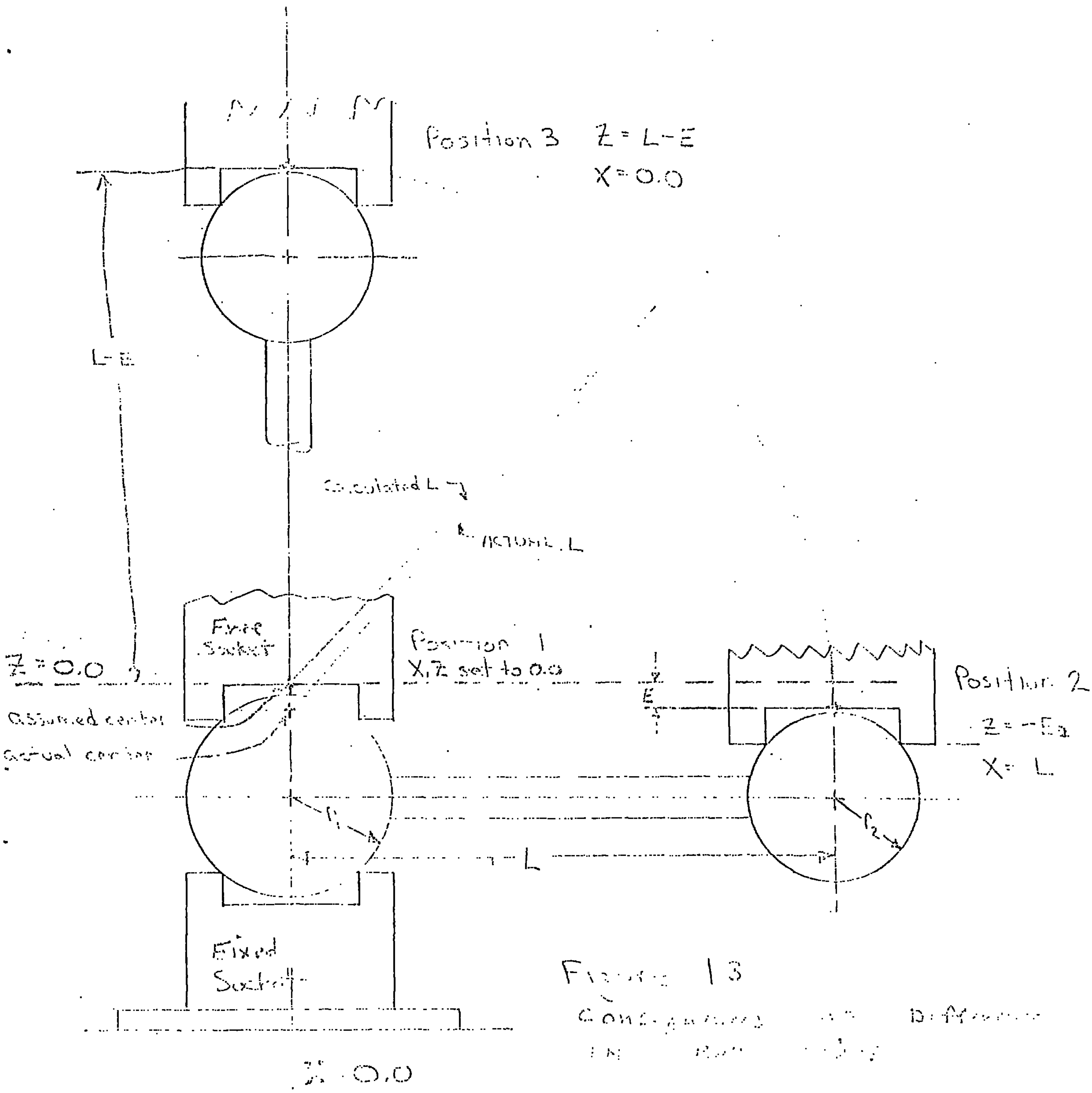


Figure 13
Consequences of Difference in Radii

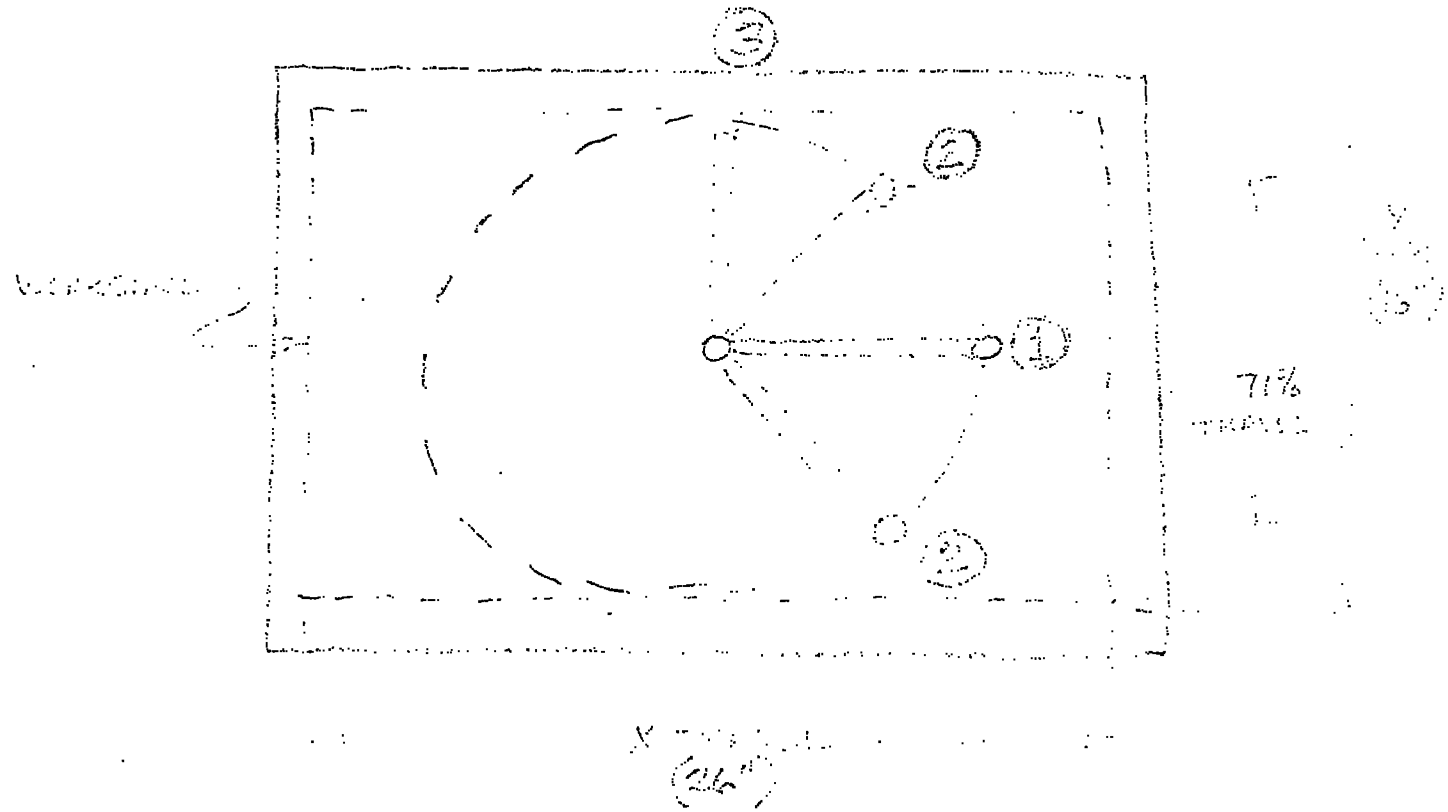


FIG. 14

[illegible]

[illegible] sensitivity For 360° [illegible]

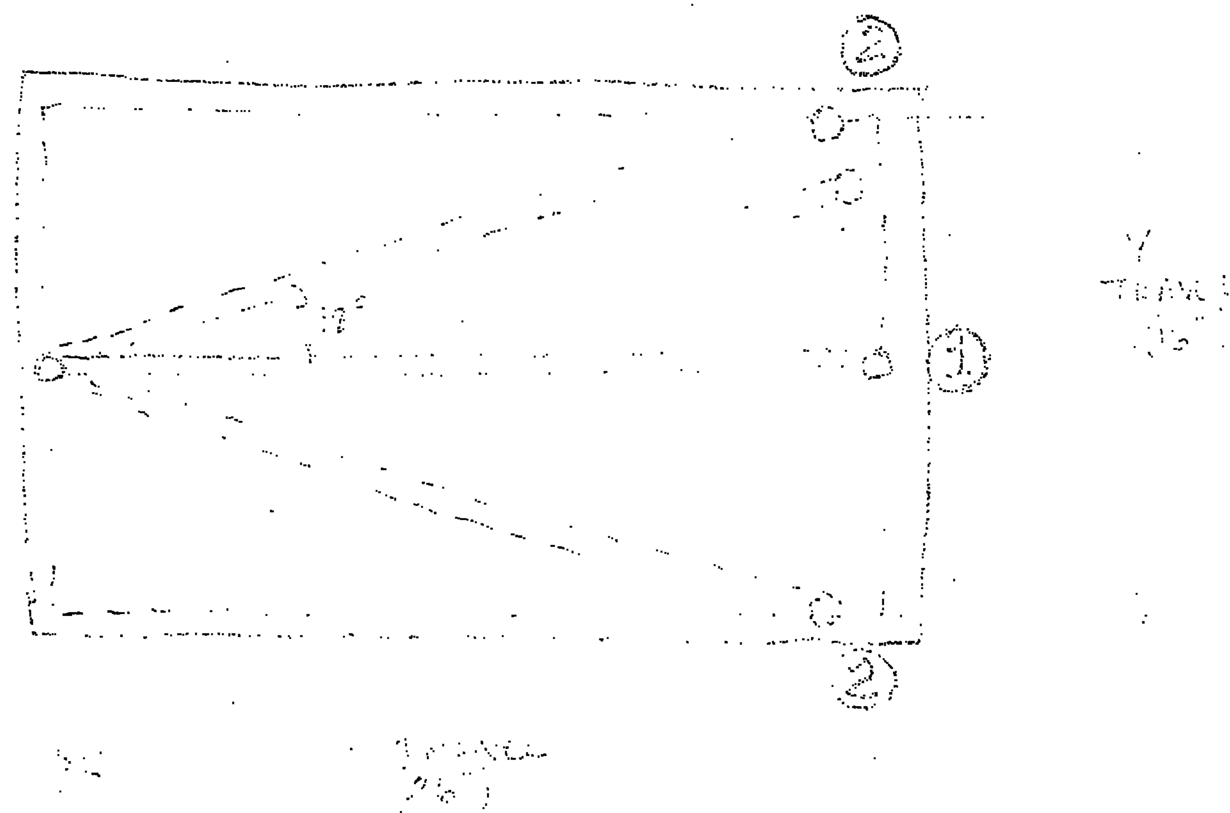
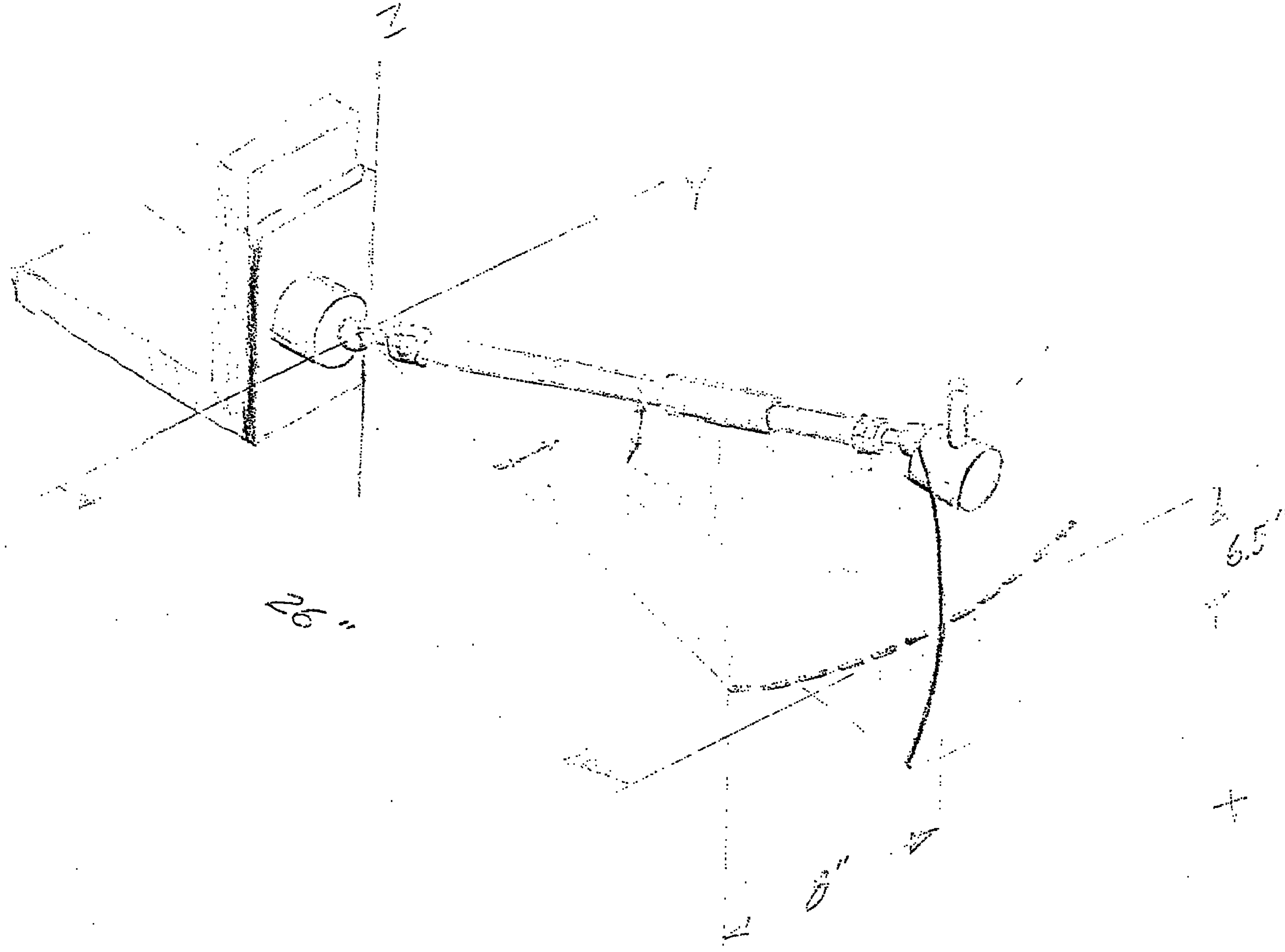


FIG. 15

New Setup For Squareness Testing


Z
Y
26"
6.5"
8"

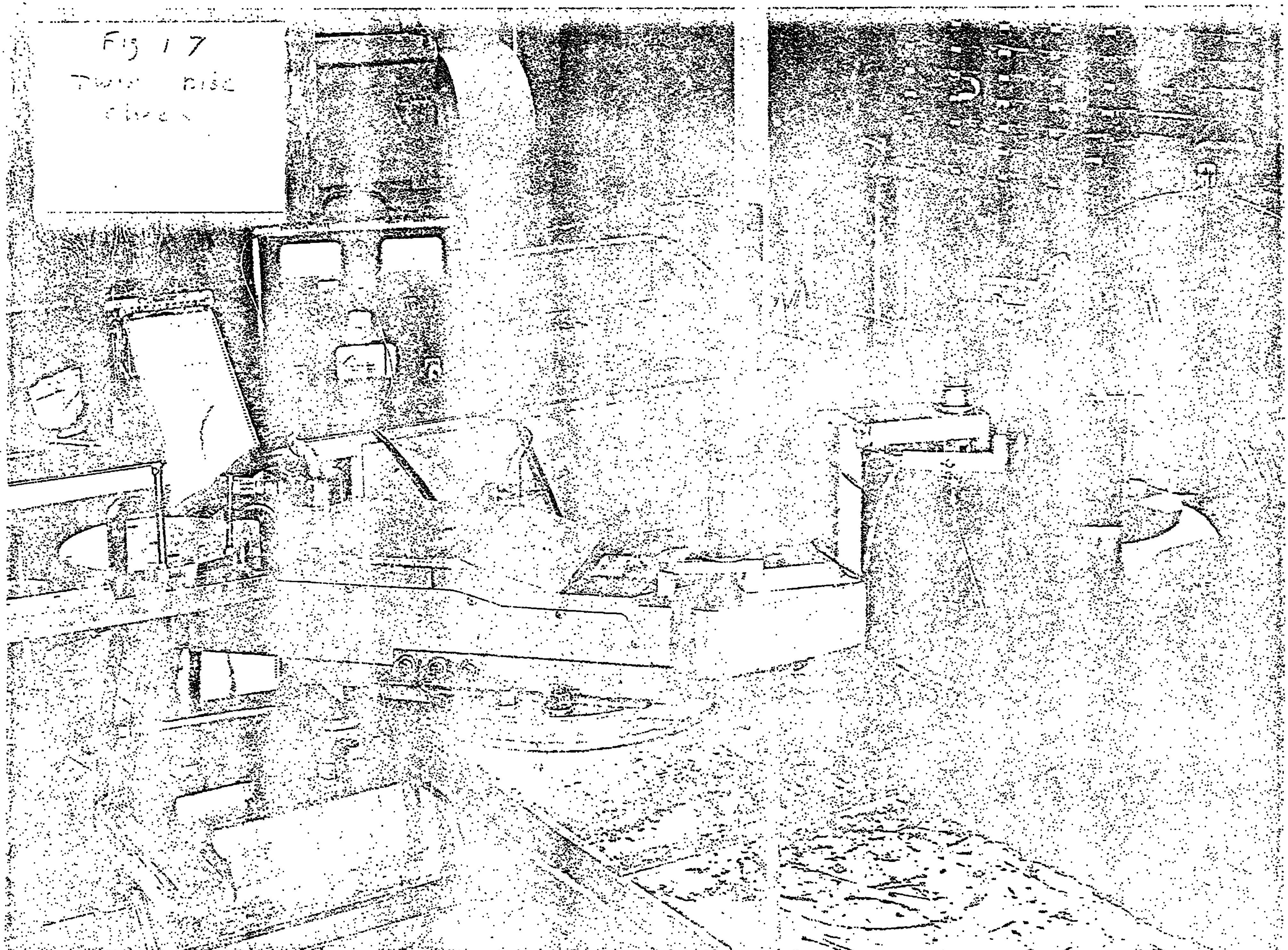


Fig 17
Twin Disc
[illegible]

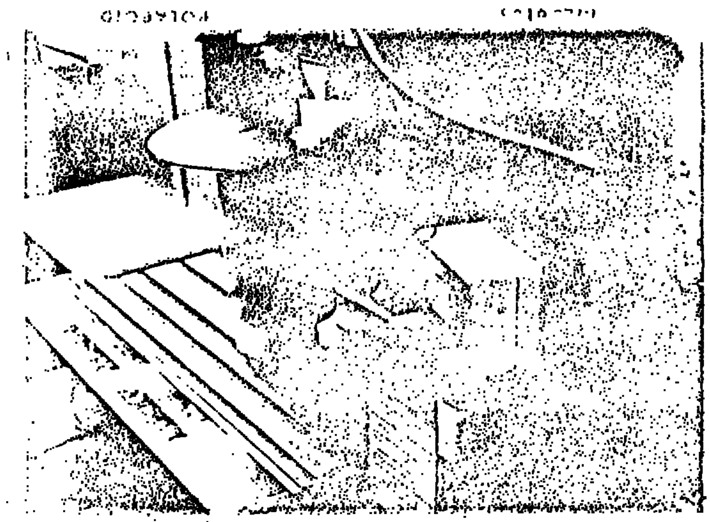
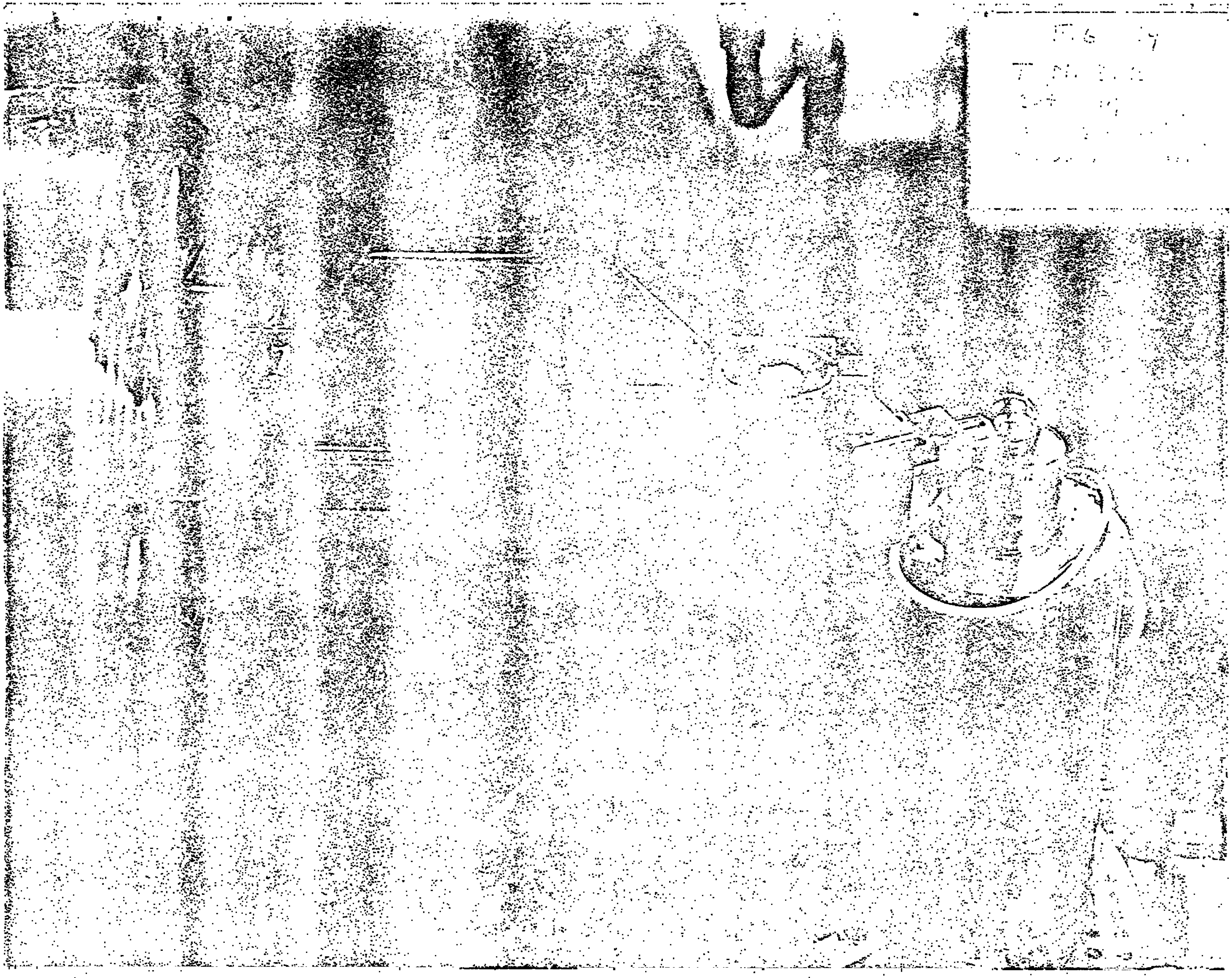


Fig 18

Rotating stylus [illegible]

360° Disc check



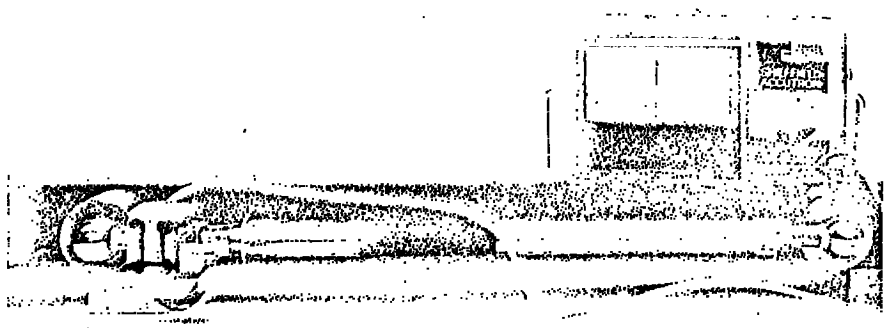


Fig 20

SAG TEST OF T.M.B.B.
Horizontal Position

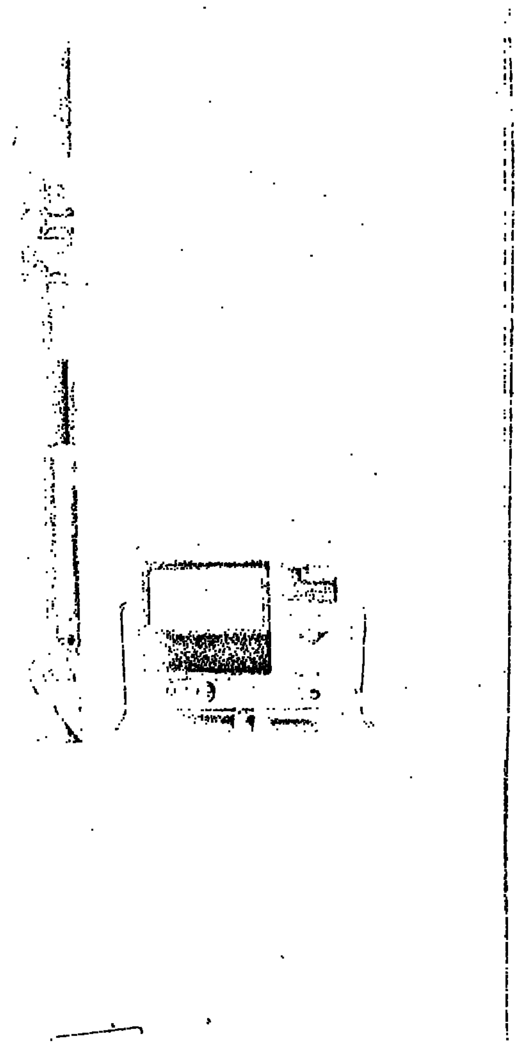


Fig 21

Sag Test of T.M.E.G.

Vertical Position Flexure

on Top

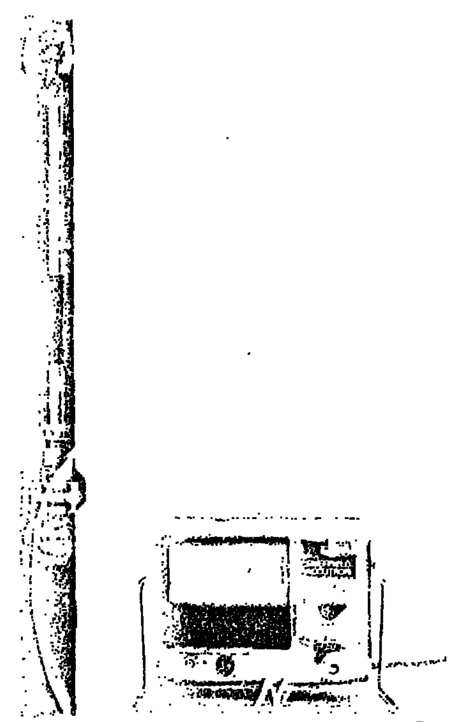


Fig 22
Sag Test of T. M. B. B
Vertical Position Flexure
on the Bottom

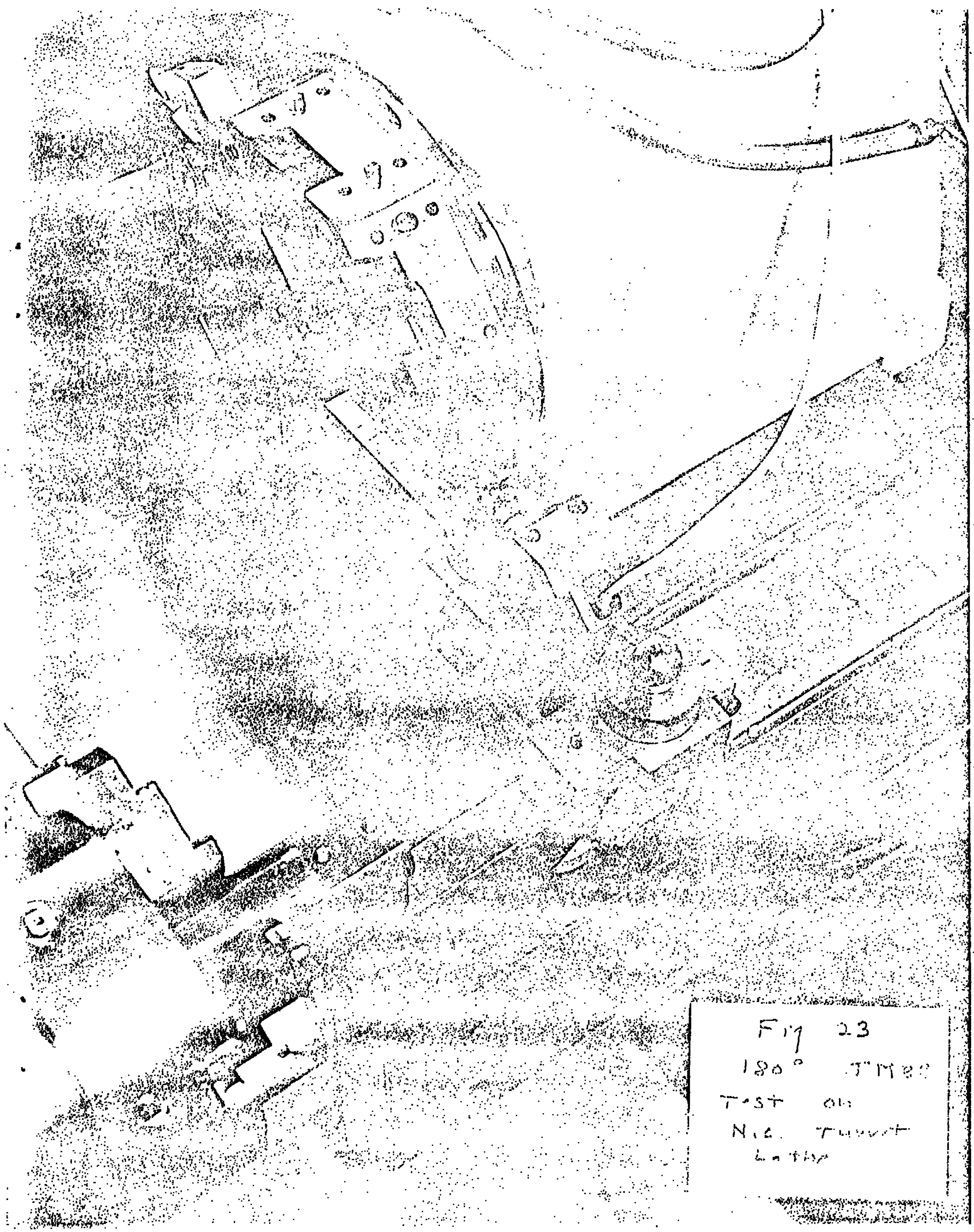


Fig 23
180° Times
Test on
No. 4 Turret
Lathe

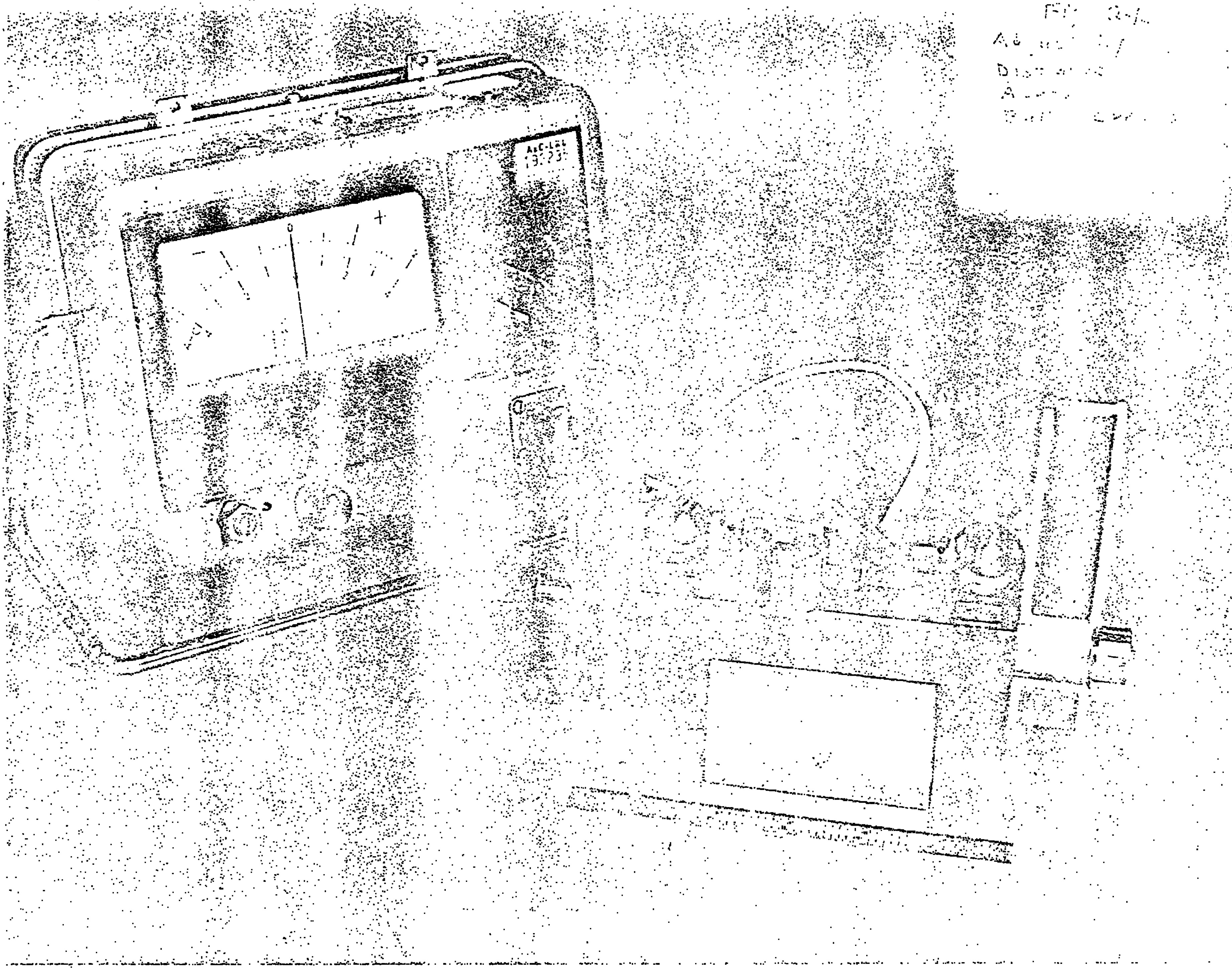


Fig 25

180°